In-Flight Observations of Long-Term Single Event Effect (SEE) Performance on X-ray Timing Explorer (XTE) Solid-State Recorders (SSRs)

Christian Poivey and George Gee
SGT, Inc.
NASA GSFC, Code 561.4
Greenbelt, MD 20771 USA
cpoivey@pop500.gsfc.nasa.gov,
ggee@pop900.gsfc.nasa.gov

Kenneth A. LaBel and Janet L. Barth
Code 561.4, Radiation Effects Branch
NASA GSFC
Greenbelt, MD 20771 USA
Kenneth.A.LaBel@nasa.gov
Janet.L.Barth@nasa.gov

Abstract—**We present multi-year Single Event Upset (SEU) flight data on Solid State Recorder (SSR) memories for the X-ray Timing Explorer (XTE) NASA mission. Actual SEU rates are compared to the predicted rates based on ground test data and environment models.**

I. INTRODUCTION

This paper presents Single Event Upset (SEU) in-flight data on Solid-State Recorders (SSRs) that have been collected over a long period of time for the NASA X-ray Timing Explorer (XTE) mission. Single Event Effects (SEE) flight data on solid-state memories give an opportunity to study the behavior in space of SEE-sensitive commercial memory devices. The actual SEU rates can be compared with the calculated rates based on environment models and ground test data. The SEE mitigation schemes can also be evaluated in actual implementation. A significant amount of data has already been published concerning observed SEE effects on memories in space. However, most of the data presented cover either a short period of time or a small number of devices. The data presented here have been collected on a large number of devices during 8 years. This allows statistically significant analysis of the effect of space weather fluctuations on SEU rates and the effectiveness of SEE countermeasures used. This is one of the first data sets that shows data during both solar maximum and solar minimum conditions.

II. MISSION AND SSR DESCRIPTION

XTE measures the variability of X-ray sources. It was launched on December 30, 1995, and put into a low-earth orbit at an altitude of 580 km with an inclination of 23 degrees. Since its launch, XTE has lost altitude. Its average altitude in May 2004 was 500 km.

XTE carries one SSR capable of storing up to 1 Gbit of science data. The SSR contains 140 Mbit of memory and is organized as 28 Mword of 40 bits size (32 bits of data, 8 bits of code). The SEU mitigation scheme is the Hamming Error and Detection and Correction Code (EDAC). The Hamming EDAC code is capable of correcting a single bit error in a word, and detecting a double bit error. In addition to EDAC, the memories are kept free from the accumulation of SEUs by a scrubbing. Each memory word is regularly read, corrected, and written back in turn every 25 minutes. The SEU information is gathered by telemetry at 32-second intervals. The SSR uses 1120 128Kx8 Static Random Access Memories (SRAM) HM628128 from Hitachi.

III. IN-FLIGHT DATA

XTE SEU data have been collected from June 1996 to May 2004. Fig. 1 shows the monthly sunspot numbers for the past 15 years [1]. XTE flight starts at the minimum of the solar cycle, approximately at the transition from cycle 22 to cycle 23. Then, the solar activity increases to reach a peak from 2002 to 2003. The most recent data collected correspond to the decrease of solar activity. The data have been collected during a period that covers both the minimum and the maximum of the solar cycle.
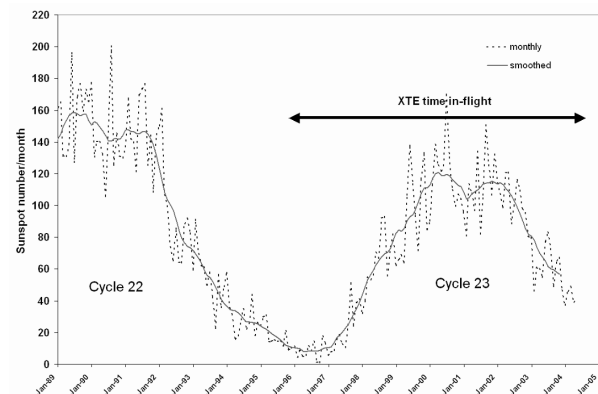

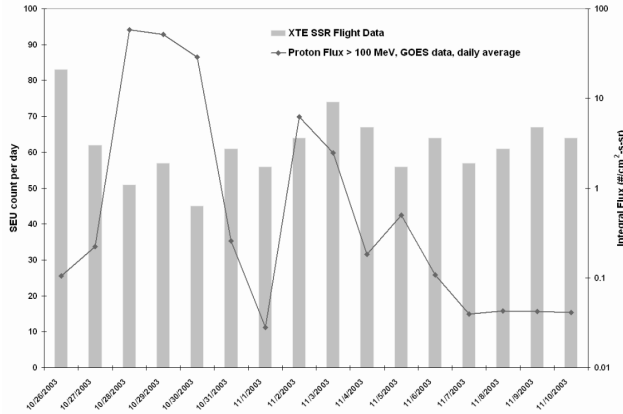Fig. 1. Monthly sunspot numbers for the past 15 years [1].

Fig. 2. Solar proton flux measurement by GOES spacecraft [2] during the Halloween 2003 solar event and number of SEU observed on XTE SSR.

Flight data show that all SEUs occur when the spacecraft goes through the trapped proton belt in the South Atlantic Anomaly (SAA) and that no increase in the upset count was observed during the large solar events that occurred during the current solar maximum period. An example is shown in Fig. 2 for the Halloween 2003 solar particle event. Even though the high-energy, greater than 100 MeV solar proton fluxes outside the magnetosphere measured by the GOES spacecraft [2] increased by orders of magnitude, the numbers of observed SEUs do not vary significantly. This is because only particles with very high energies can penetrate the magnetosphere to reach low altitude, low inclination orbits such as XTE. Fig. 3 illustrates this geomagnetic field cutoff effect for typical low altitude orbits.

Fig. 4 shows the monthly average of the daily upset count. A general decrease of the upset count with time is evident. The average SEU count per day was 229 in July 1996. It reached a minimum of 55 in April 2003. Since April 2003 the number of SEUs is increasing slightly. The SEU count per day in May 2004 was 64.
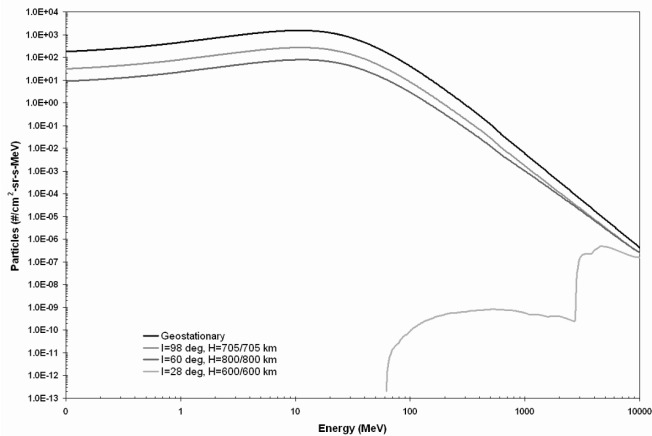

Fig. 3. Differential solar proton fluxes behind 100 mils of Aluminum shielding for different orbits, CREME96 worst-day model [3, 4]
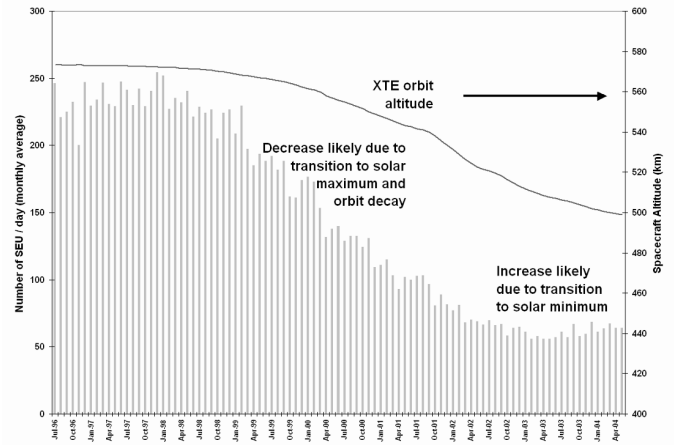

Fig. 4. Daily upset count (monthly average) and spacecraft altitude from June 1996 to May 2004.

The decrease is well correlated with the increased solar activity during the solar cycle and the decrease in spacecraft altitude. As both parameters vary at the same time, it is difficult to evaluate their respective impact. However, since April 2003 the SEU counts do not decrease any more while the spacecraft altitude is still decreasing steadily (see Fig. 4). This indicates that the solar activity plays a significant role.

Fig. 5 shows the > 30 MeV orbit average trapped proton fluxes versus the spacecraft altitude for solar minimum and solar maximum activity. These fluxes were obtained with the AP8 trapped proton model [5]. This model is a static model that does not describe the temporal behavior of fluxes apart the separate versions for solar maximum and minimum conditions. It represents omnidirectional, integral intensities that one would expect to accumulate on average over a few months period of time [3, 6]. The trapped proton fluxes are lower during solar maximum because the atmosphere of the Earth swells thereby increasing the loss of protons from the SAA through increased collisions.
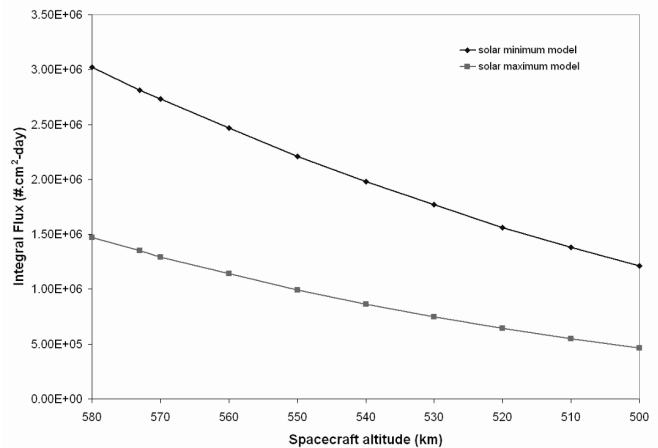

Fig. 5. Trapped proton fluxes >30 MeV behind 200 mils of Aluminum shielding versus spacecraft altitude for solar minimum and solar maximum activity, AP8 model [5].
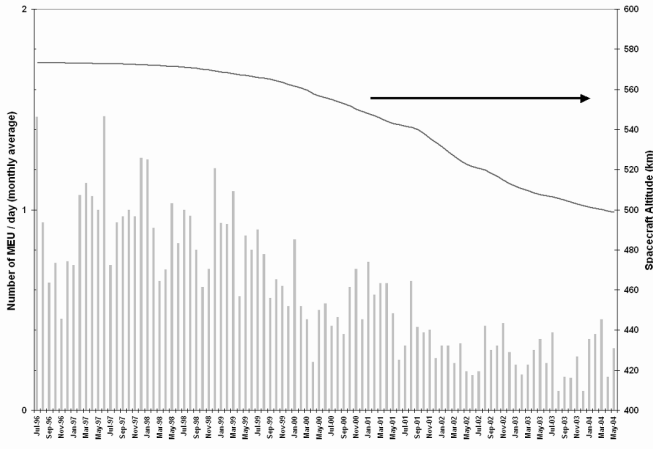
Fig. 6. Daily MEU count (monthly average) and spacecraft altitude from June 1996 to May 2004.

In Fig. 5, the fluxes decrease by a factor two to three from a 580 km altitude to a 500 km altitude. In this altitude range there is a factor of two between the fluxes at solar minimum activity and the fluxes at solar maximum activity. Therefore, the solar activity has roughly the same effects on the particle fluxes as the spacecraft altitude decay.

Single-word, Multiple Bit Upsets (MBUs) were observed. Fig 6 shows the monthly average of the daily MBU count. This number is low, from about one per day in 1996 to about one every few days in 2004. MBUs were observed on the 1M Hitachi SRAM device during heavy ion testing [7]. The cause of these MBUs is the physical organization of this memory in which one logical word consists of two sets of four bits that are physically adjacent. MBUs were also observed with protons [8].

IV. COMPARISON OF ACTUAL RATES TO PREDICTIONS

A. Ground Test Data

Figs. 7 and 8 show the heavy ion and proton induced SEU cross-section curves, respectively. Heavy ion MBU information is given in [10]. At high LET, about 37% of the SEEs are MBUs. The proton MBU cross section is $3\text{x}10^{-10}$ cm^2/device at 200 MeV [8].
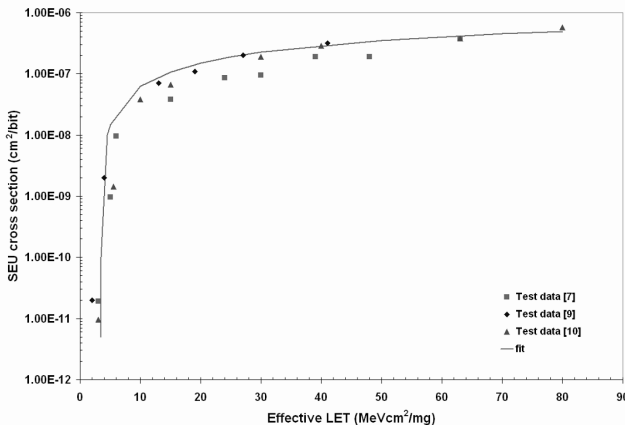

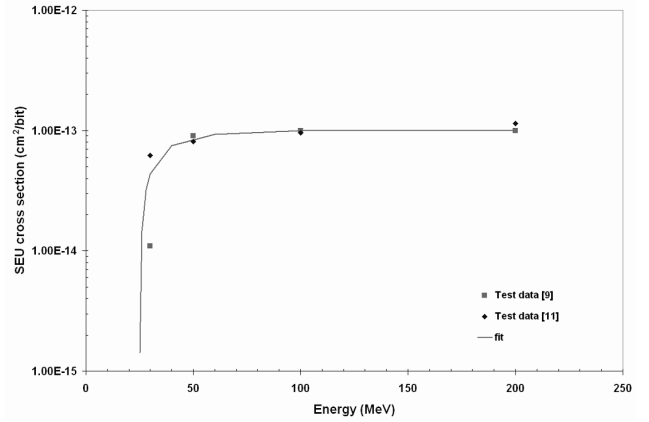Fig. 7. HM628128 heavy ion SEU cross section curve.

Fig. 8. HM628128 proton SEU cross section curve.

B. Prediction Results

Predictions were performed with CREME96 [4] using a Weibull fit of test data and assuming a 4 μm sensitive volume thickness [12] and 200 mils Aluminum shielding thickness. Predictions were performed for different altitudes corresponding to the decreasing spacecraft altitude with time. Solar minimum models were used for the years 1996 to 1998, and solar maximum models were used for the years 1999 to 2003.

Prediction results show that all SEUs are induced by trapped protons and that Solar Particle Events (SPE) do not have any impact on the SEU count as it has been observed in flight. Fig. 9 compares the SEU prediction with the actual SEU counts in flight. The predictions give the actual SEU counts within a factor of 2.

Prediction results also show that the effects of decreasing altitude and solar modulation are equivalent. In the 500 km to 580 km altitude range, the ratio of the SEU number for solar minimum condition to the SEU number for solar maximum condition is about a factor of 2. The ratio of the number of errors at 580 km altitude to the number of SEUs at 500 km altitude for the solar minimum condition is about 2.5. The ratio of the number of error at 580 km altitude to the number of SEUs at 500 km altitude for the solar maximum condition is about 3.
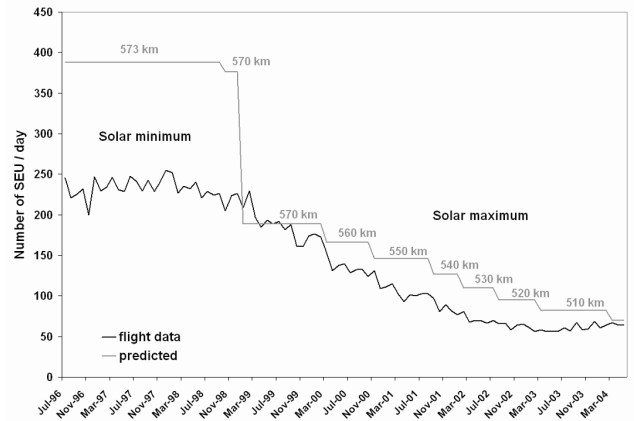

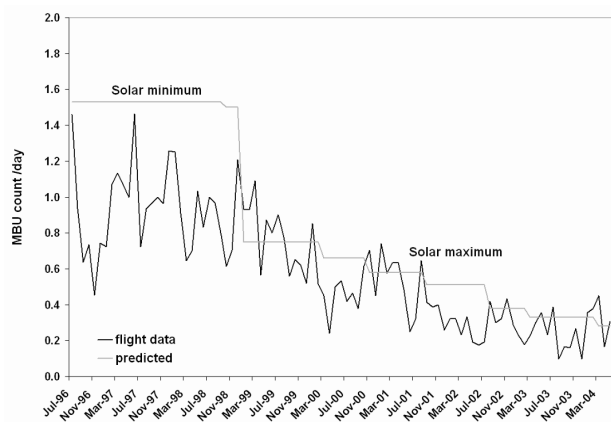Fig. 9. Comparison of actual SEU counts with predictions.

Fig. 10. Comparison of actual SEU counts with predictions.

Fig. 10 compares the MBU predictions with the actual MBU counts in flight. The predictions also give the actual MBU counts within a factor of 2.

The predictions are consistent with the prediction of 1 MBU per day obtained with the old version of CREME at the time of the project development [8].

MBUs will make the EDAC Hamming code fail. The worst-case observed number of MBU in flight in one day is 4. The number of downloads of SSR data to ground varies from 10 to 14 per day. If we consider an average number of 12 downloads per day, the worst case Bit Error Rate (BER) is about 2×10^{-9} bit per day. This figure is orders of magnitude below the acceptable mission BER of 1×10^{-7} bit per day [8, 13].

V. Conclusion

Long term observations of flight data such as the one presented here show the effect of space weather fluctuations on SEU rates. We can see in the data presented here that the modulation of particle fluxes due to solar activity has a significant impact on the SEU count.

EDAC techniques are very efficient in mitigating SEUs in SSR applications as long as multiple errors induced by a single particle do not create multiple upsets in a data word. EDAC failures were observed in flight. Their number is low, less than one per day in average, and do not impact the quality of XTE science data.

REFERENCES

[1] Sunspot and Space Weather information pages, Solar Influences Data Analysis Center (SIDC) archives, http://sidc.oma.be
[2] NOAA Space Physics Interactive Data Resource (SPIDR) archives, http://spidr.ngdc.noaa.gov
[3] J. L. Barth, ""Modeling space radiation environments," 1997 IEEE NSREC short course, Snowmass, Jul. 1997.
[4] A. J. Tylka, J. H. Adams, P. R. Boberg, W. F. Dietrich, E. O. Flueckiger, E. L. Petersen, M. A. Shea, D. F. Smart, and E. C. Smith, "CREME 96: A revision of the cosmic ray effects on micro-electronics code," IEEE Trans. on Nuc. Sci., vol. 44, no. 6, pp. 2150-2160, Dec. 1997.
[5] D. M. Sawyer and J. I. Vette, "AP-8 trapped proton environment for solar maximum and solar minimum," NSSDC/WDC-A-R&S, 76-06, NASA Goddard Space Flight Center, Greenbelt, MD, Dec. 1976.
[6] E. J. Daly, J. Lemaire, D. Heynderickx, and D. J. Rodgers, "Problems with models of the radiation belts," IEEE Trans. on Nuc. Sci., vol. 43, no. 2, pp. 403-415, Apr. 1996.
[7] R. Koga, S.D. Pinkerton, T.J. Lie, and K.B. Crawford, "Single-word multiple bit upsets in static random access devices," IEEE Trans. Nuc. Sci., vol. 40, no. 6, pp. 1941-1946, Dec. 1993.
[8] Ken LaBel, private communication.
[9] R. Harboe-Sorensen, E.J. Daly, and L. Adams, "Observation and prediction of SEU in Hitachi SRAMs in low altitude polar orbits," IEEE Trans. Nuc. Sci., vol. 40, no. 6, pp. 1498-1504, Dec. 1993.
[10] R. Koga, W.R. Crain, K.B. Crawford, D.D. Lau, and S.D. Pinkerton, "On the suitability of non-hardened high density SRAMs for space applications," IEEE Trans. Nuc. Sci., vol. 38, no. 6, pp. 1507-1513, Dec. 1991.
[11] S. Duzellier and D. Falguere, "Heavy ion/proton test results on high integrated memories," 1993 IEEE Radiation Effect Data Workshop Proceedings, pp. 36-42, 1993.
[12] C. Inguibert, S. Duzellier, R. Ecoffet, L. Guibert, J. Barak, ans M. Chabot, "Using a carbon beam as a probe to extract the thickness of sensitive volumes," RADECS 1999 Proceedings, pp. 180-187, 2000.
[13] A. K. Moran, K. A. LaBel, C. M. Seidleck, P. Marshall, J. L. Barth, and C. Marshall, "In-flight analysis of enabling technology," 1997 IEEE Aerospace Conference Proceedings, pp. 333-342, 1997.